

VERY LARGE ARRAY PLUS PIE TOWN ASTROMETRY OF 46 RADIO STARS

D. A. BOBOLTZ,¹ A. L. FEY,¹ W. K. PUATUA,¹ N. ZACHARIAS,¹ M. J. CLAUSSEN,² K. J. JOHNSTON,¹ AND R. A. GAUME¹

Received 2006 June 27; accepted 2006 October 11

ABSTRACT

We have used the Very Large Array, linked with the Pie Town Very Long Baseline Array antenna, to determine astrometric positions of 46 radio stars in the International Celestial Reference Frame (ICRF). Positions were obtained in the ICRF directly through phase referencing of the stars to nearby ICRF quasars whose positions are accurate at the 0.25 mas level. Radio star positions are estimated to be accurate at the 10 mas level, with position errors approaching a few milliarcseconds for some of the stars observed. Our measured positions were combined with previous measurements taken from as early as 1978 to obtain proper-motion estimates for all 46 stars with average uncertainties of ≈ 1.7 mas yr^{-1} . We compared our radio star positions and proper motions with the *Hipparcos* Catalogue data and found consistency in the reference frames produced by each data set on the 1σ level, with errors of ~ 2.7 mas per axis for the reference frame orientation angles at our mean epoch of 2003.78. No significant spin is found between our radio data frame and the *Hipparcos* Celestial Reference Frame, with the largest rotation rates of $+0.55$ and -0.41 mas yr^{-1} around the x - and z -axes, respectively, with 1σ errors of 0.36 mas yr^{-1} . Thus, our results are consistent with a non-rotating *Hipparcos* frame with respect to the ICRF.

Key words: astrometry — binaries: close — radio continuum: stars — techniques: interferometric

1. INTRODUCTION

The current realization of the International Celestial Reference Frame (ICRF) is defined by the positions of 212 extragalactic objects derived from Very Long Baseline Interferometry (VLBI) observations (Ma et al. 1998; Gambis 1999, p. 87; Fey et al. 2004). This VLBI realization of the ICRF is currently the International Astronomical Union (IAU)—sanctioned fundamental celestial reference frame. At optical wavelengths, the *Hipparcos* Catalogue (Perryman et al. 1997) now serves as the primary realization of the celestial reference frame. The link between the *Hipparcos* Catalogue and the ICRF was accomplished through a variety of ground-based and space-based efforts (Kovalevsky et al. 1997), with the highest weight given to VLBI observations of 12 radio stars by Lestrade et al. (1999). The standard error of the alignment was estimated to be 0.6 mas at epoch 1991.25, with an estimated error in the system rotation of 0.25 mas yr^{-1} per axis (Kovalevsky et al. 1997).

At the epoch of our most recent radio star observations (2004.80) the formal error associated with the *Hipparcos*-ICRF frame link is estimated to be ~ 3.4 mas. Due to errors in the proper motions, the random position errors of individual *Hipparcos* stars increased from ~ 1 mas in 1991 to ~ 12 mas at the time of our most recent observations. Such uncertainties in the frame rotation and the astrometry of individual sources can combine to seriously limit the ability to align high-resolution multiwavelength data on a particular source, thus restricting the astrophysical interpretation of potentially interesting objects.

In this paper we present X-band radio observations of 46 radio stars using the Very Large Array (VLA) in the A configuration linked by fiber optic transmission line to the Very Long Baseline Array (VLBA) antenna located in Pie Town, New Mexico. Both the VLA and VLBA are maintained and operated by the National Radio Astronomy Observatory.³ The VLA plus Pie Town

(VLA+PT) link (Claussen et al. 1999) is a valuable tool for radio star astrometry because it provides the high sensitivity of the VLA with nearly twice the resolution of the VLA A configuration alone for high-declination sources.

The work described herein represents a continuation of a long-term program (since 1978) to obtain accurate astrometric radio positions and proper motions for ~ 50 radio stars that can be used to connect the current ICRF to future astrometric satellite (e.g., *Gaia* and *Space Interferometry Mission PlanetQuest*) reference frames. These stars were originally selected to be observable at both optical and radio wavelengths, with detectability in the radio being the primary limitation. Quiescent radio flux densities are on the order of 1–10 mJy, with occasional flares of emission >100 mJy. All of the stars have been observed with *Hipparcos* and have spectral types ranging from A to M and visual magnitudes ranging from 0.58 to 10.80. Many of the stars are RS CVn and Algol-type binary systems. Early observations in the program were used to connect the radio frame to the FK4 optical reference frame (Johnston et al. 1985), while later observations were used to link the radio-based ICRF to the *Hipparcos* optical reference frame (Johnston et al. 2003).

The astrometric positions derived from the three epochs of VLA+PT observations are combined with previous VLA (Johnston et al. 1985, 2003), VLA+PT (Boboltz et al. 2003), and Multi-Element Radio Linked Interferometer Network (MERLIN; Fey et al. 2006) positions to determine updated proper motions, $\mu_\alpha \cos \delta$ and μ_δ , for all 46 sources. Position and proper-motion results obtained for the 46 stars are compared with the corresponding *Hipparcos* values as a measure of the accuracy of our results. Finally, position and proper-motion differences relative to the *Hipparcos* values are computed in order to determine the current (epoch 2004) spin alignment of the *Hipparcos* frame with respect to the ICRF.

2. OBSERVATIONS AND REDUCTION

The VLA+PT radio observations occurred over three epochs: 2003 June 6–7, 2003 September 9–10, and 2004 October 18–19. For the first two epochs, designated experiments AF399a and AF399b, observations occurred over a 24 hr period with 24 and

¹ US Naval Observatory, Washington, DC, USA.

² National Radio Astronomy Observatory, Socorro, NM, USA.

³ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

| | | |
|---|------------------------------------|-------------------------------------|
| 1. REPORT DATE MAR 2007 | 2. REPORT TYPE N/A | 3. DATES COVERED - |
| 4. TITLE AND SUBTITLE Very Large Array Plus Pie Town Astrometry of 46 Radio Stars | | |
| 5a. CONTRACT NUMBER | | |
| 5b. GRANT NUMBER | | |
| 5c. PROGRAM ELEMENT NUMBER | | |
| 6. AUTHOR(S) | | |
| 5d. PROJECT NUMBER | | |
| 5e. TASK NUMBER | | |
| 5f. WORK UNIT NUMBER | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Naval Observatory Washington, DC | | |
| 8. PERFORMING ORGANIZATION REPORT NUMBER | | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | |
| 10. SPONSOR/MONITOR'S ACRONYM(S) | | |
| 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited | | |
| 13. SUPPLEMENTARY NOTES | | |
| 14. ABSTRACT | | |
| 15. SUBJECT TERMS | | |
| 16. SECURITY CLASSIFICATION OF: | | |
| a. REPORT unclassified | b. ABSTRACT unclassified | c. THIS PAGE unclassified |
| 17. LIMITATION OF ABSTRACT SAR | | |
| 18. NUMBER OF PAGES 11 | | |
| 19a. NAME OF RESPONSIBLE PERSON | | |

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

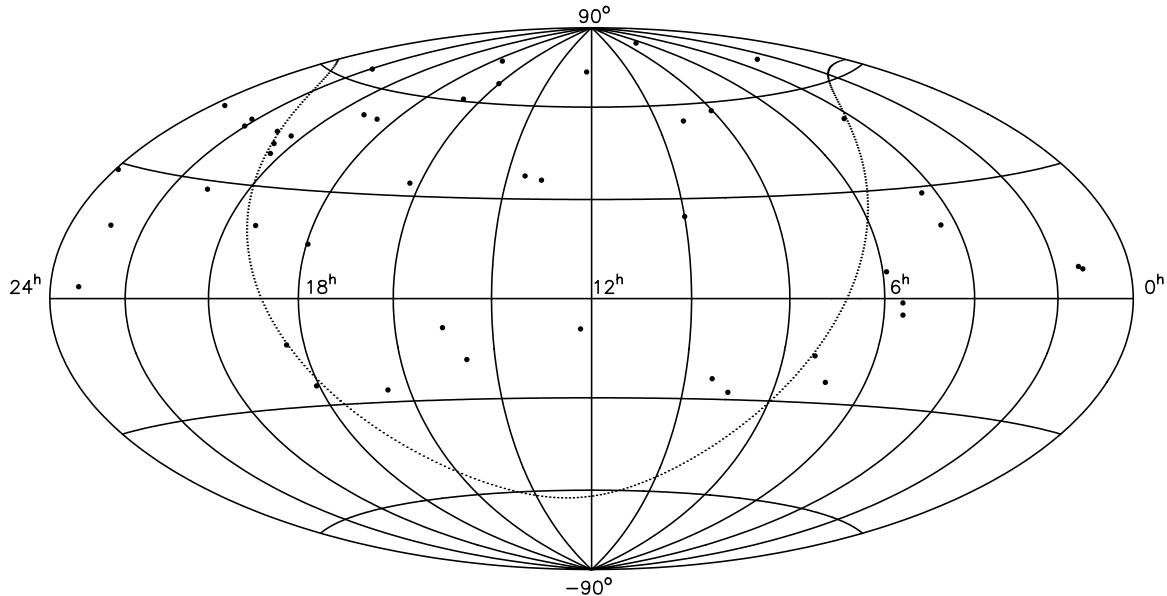


FIG. 1.—Distribution of the 46 observed radio stars plotted on an Aitoff equal-area projection of the celestial sphere. The dotted line represents the Galactic equator.

26 stars observed, respectively. The third epoch was observed over a 10 hr period in which 10 stars not detected in the previous two sessions were reobserved. Data for all three epochs were recorded in dual circular polarization using two adjacent 50 MHz bands centered on rest frequencies of 8460.1 and 8510.1 MHz. The sky distribution of the 46 radio stars detected is shown in Figure 1.

Observations were conducted in a phase-referencing mode by rapidly switching between the star and a nearby ICRF reference source. Listed in Table 1 are the radio star targets along with their associated ICRF calibrators. Also shown in the table are the ICRF positions for each calibrator, the ICRF category, and the separation in degrees between the target and the reference source. Positions for the ICRF reference sources are estimated to be accurate to the 0.25 mas level. For the first two epochs, typical target-calibrator scans lasted 8 minutes with a 2 minute cycle time (90 s on the star and 30 s on the calibrator) for approximately four cycles per scan. For the third epoch the cycle times were increased to 3 minutes (140 s on the star and 40 s on the calibrator) with scans lasting 12 minutes, again resulting in four cycles per scan. Over the course of an experiment, five to eight scans were recorded for each target-calibrator pair over a wide range of hour angles. In addition, periodic scans on the source 3C 48 were performed for the purpose of absolute flux density calibration.

Data were calibrated using the standard routines within the Astronomical Image Processing System (AIPS). The absolute flux density scale was established using the values calculated by AIPS for 3C 48 with the proper u - v restrictions applied. Phase calibration was accomplished through transfer of the phases from the reference source to the target source data. From the calibrated data, images were produced for each scan on each target for a total of up to eight images per star per epoch of observations. Average rms noise levels in the CLEANed images from the individual scans were 0.1, 0.09, and 0.04 mJy beam $^{-1}$ for AF399a, AF399b, and AJ315, respectively. Recall that scan times were increased in experiment AJ315 to increase the probability of detecting previously undetected stars from AF399a and AF399b. In addition, a summed image of each star was produced that included data from all scans on the source. Two-dimensional (2-D) Gaussian functions were fit to the emission in the images using

the AIPS task JMFIT. For the three experiments, detection rates were 19 out of 24 stars (79%) in AF399a, 21 out of 26 (81%) in AF399b, and 7 out of 11 (64%) in AJ315. For comparison, the detection rate for our VLA+PT radio star pilot study (Boboltz et al. 2003) was 19 out of 19 stars (100%); however, there we purposely tried to select radio stars with high flux densities based on previous observations.

3. RESULTS AND DISCUSSION

3.1. Source Positions

Final estimation of source positions and uncertainties was performed outside of AIPS using the results of the 2-D Gaussian fits to the images produced from the observations. Table 2 lists the source positions and associated uncertainties determined for the 46 stars detected over the three epochs. Note that the star HD 193793 appears twice, since it was observed in two experiments, AF399a and AJ315. Because the radio stars were directly referenced to ICRF quasar calibrators using the phase-referencing technique, the positions listed in Table 2 are given directly in the ICRF. Also denoted in the last two columns of Table 2 are the epoch of observation and the number of successful/total observations (scans), which were used in the estimation of position uncertainties for each source. Final positions reported in Table 2 are simply the JMFIT least-squares position estimates from the summed image of each star. The 1σ position uncertainties listed in the table were estimated using a procedure similar to that described in Fey et al. (2006) and summarized below, depending on whether the source was detected in one or more individual scans.

If a given star was detected in more than one scan, then an rms scatter in the JMFIT scan-based positions weighted by the JMFIT formal errors was computed. The uncertainty in the position reported for each star is then the root sum square (rss) of this weighted rms (wrms) position scatter and the value of the JMFIT least-squares formal uncertainty from the fit to the summed image of the source. The addition of the wrms position scatter was meant to conservatively account for possible systematic errors introduced into the positions by factors such as the variable troposphere. The position uncertainties listed in Table 2 represent the resulting rss values for sources detected in more than one observation.

TABLE 1
OBSERVED RADIO STARS AND CORRESPONDING ICRF CALIBRATOR SOURCES

| Star Name | Hipparcos Number | ICRF Calibrator | ICRF Category ^a | α (J2000.0) ^b | δ (J2000.0) ^b | Separation (deg) |
|----------------------|------------------|-----------------|----------------------------|---------------------------------|---------------------------------|------------------|
| UV Psc | 5980 | 0119+041 | C | 01 21 56.861699 | 04 22 24.73436 | 2.7 |
| HD 8357 | 6454 | 0119+041 | C | 01 21 56.861699 | 04 22 24.73436 | 3.1 |
| RZ Cas | 13133 | 0224+671 | D | 02 28 50.051459 | 67 21 03.02926 | 2.9 |
| B Per | 20070 | 0355+508 | O | 03 59 29.747262 | 50 57 50.16151 | 3.0 |
| HD 283572 | 20388 | 0430+289 | N | 04 33 37.829860 | 29 05 55.47701 | 2.7 |
| T Tau N | 20390 | 0409+229 | N | 04 12 43.666851 | 23 05 05.45299 | 4.2 |
| HD 37017 | 26233 | 0539-057 | D | 05 41 38.083384 | -05 41 49.42839 | 2.0 |
| ϵ Ori | 26311 | 0539-057 | D | 05 41 38.083384 | -05 41 49.42839 | 4.7 |
| α Ori | 27989 | 0529+075 | C | 05 32 38.998531 | 07 32 43.34586 | 5.6 |
| SV Cam | 32015 | 0615+820 | D | 06 26 03.006188 | 82 02 25.56764 | 0.6 |
| HD 50896 | 33165 | 0646-306 | C | 06 48 14.096441 | -30 44 19.65940 | 6.9 |
| R CMa | 35487 | 0727-115 | O | 07 30 19.112472 | -11 41 12.60048 | 5.4 |
| 54 Cam | 39348 | 0749+540 | D | 07 53 01.384573 | 53 52 59.63716 | 3.7 |
| TY Pyx | 44164 | 0919-260 | O | 09 21 29.353874 | -26 18 43.38604 | 5.1 |
| XY UMa | 44998 | 0850+581 | D | 08 54 41.996385 | 57 57 29.93928 | 4.1 |
| IL Hya | 46159 | 0919-260 | O | 09 21 29.353874 | -26 18 43.38604 | 2.6 |
| DH Leo | 49018 | 0953+254 | O | 09 56 49.875361 | 25 15 16.04977 | 1.0 |
| HU Vir | 59600 | 1145-071 | C | 11 47 51.554036 | -07 24 41.14109 | 6.5 |
| DK Dra | 59796 | 1053+704 | C | 10 56 53.617492 | 70 11 45.91585 | 6.7 |
| RS CVn | 64293 | 1315+346 | C | 13 17 36.494189 | 34 25 15.93266 | 2.1 |
| HR 5110 | 66257 | 1315+346 | C | 13 17 36.494189 | 34 25 15.93266 | 4.4 |
| RV Lib | 71380 | 1430-178 | C | 14 32 57.690643 | -18 01 35.24885 | 0.7 |
| δ Lib | 73473 | 1511-100 | C | 15 13 44.893444 | -10 12 00.26435 | 3.6 |
| AG Dra | 78512 | 1642+690 | D | 16 42 07.848514 | 68 56 39.75640 | 4.4 |
| σ^2 CrB | 79607 | 1611+343 | C | 16 13 41.064249 | 34 12 47.90909 | 0.4 |
| α Sco | 80763 | 1622-253 | O | 16 25 46.891639 | -25 27 38.32688 | 1.3 |
| WW Dra | 81519 | 1637+574 | D | 16 38 13.456293 | 57 20 23.97918 | 3.4 |
| 29 Dra | 85852 | 1749+701 | D | 17 48 32.840231 | 70 05 50.76882 | 4.3 |
| Z Her | 87965 | 1743+173 | D | 17 45 35.208181 | 17 20 01.42341 | 3.7 |
| 9 Sgr | 88469 | 1817-254 | C | 18 20 57.848685 | -25 28 12.58456 | 4.0 |
| FR Sct | 90115 | 1817-254 | C | 18 20 57.848685 | -25 28 12.58456 | 12.8 |
| BY Dra | 91009 | 1823+568 | D | 18 24 07.068372 | 56 51 01.49088 | 5.3 |
| HR 7275 | 94013 | 1954+513 | D | 19 55 42.738273 | 51 31 48.54623 | 7.3 |
| U Sge | 94910 | 1923+210 | C | 19 25 59.605370 | 21 06 26.16218 | 2.3 |
| V444 Cyg | 100214 | 2005+403 | O | 20 07 44.944851 | 40 29 48.60414 | 2.9 |
| HD 193793 | 100287 | 2005+403 | O | 20 07 44.944851 | 40 29 48.60414 | 4.1 |
| V729 Cyg | 101341 | 2005+403 | O | 20 07 44.944851 | 40 29 48.60414 | 4.7 |
| HD 199178 | 103144 | 2037+511 | D | 20 38 37.034755 | 51 19 12.66269 | 7.4 |
| ER Vul | 103833 | 2113+293 | D | 21 15 29.413455 | 29 33 38.36694 | 3.4 |
| VV Cep | 108317 | 2229+695 | D | 22 30 36.469725 | 69 46 28.07698 | 7.0 |
| RT Lac | 108728 | 2200+420 | O | 22 02 43.291377 | 42 16 39.97994 | 1.6 |
| AR Lac | 109303 | 2200+420 | O | 22 02 43.291377 | 42 16 39.97994 | 3.6 |
| IM Peg | 112997 | 2251+158 | O | 22 53 57.747932 | 16 08 53.56089 | 0.7 |
| SZ Psc | 114639 | 2318+049 | C | 23 20 44.856598 | 05 13 49.95266 | 3.1 |
| λ And | 116584 | 2351+456 | O | 23 54 21.680266 | 45 53 04.23653 | 3.0 |
| HD 224085 | 117915 | 2337+264 | O | 23 40 29.029462 | 26 41 56.80485 | 3.8 |

^a ICRF source category (Ma et al. 1998; Gambis 1999, p. 87; Fey et al. 2004): D, defining; C, candidate; O, other; N, new in ICRF extension 1.

^b ICRF extension 1 source positions (Gambis 1999, p. 87). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

If the source was detected in only a single scan, then the reported position uncertainties in Table 2 were estimated by taking the rss of the JMFIT formal position error from the summed image and the average value of the wrms position scatter for all sources with multiple observations in the particular epoch in which the star was observed. There were only three such sources, UV Psc (HIP 5980), SV Cam (HIP 32015), and HR 7275 (HIP 94013), in which the average scatter had to be used, one source in each experiment. For the three experiments, AF399a, AF399b, and AJ315, the average wrms values of position scatter for stars detected in more than one observation were 7.3, 12.1, and 6.3 mas in $\alpha \cos \delta$ and 9.4, 11.1, and 9.9 mas in δ , respectively. Again, this rss step

was meant to conservatively account for possible systematic errors in the measured positions.

Table 3 compares the uncertainties in our VLA+PT positions with the corresponding *Hipparcos* uncertainties and lists the rss combined uncertainties for each star. The *Hipparcos* uncertainties have been updated to the epoch of our observations using the reported *Hipparcos* proper-motion errors. Our errors compare favorably with the *Hipparcos* position errors updated to our epoch. The average and median position uncertainties for all 46 stars detected in the VLA+PT observations are 10.2 and 9.2 mas, respectively, in $\alpha \cos \delta$ and 11.5 and 11.3 mas, respectively, in δ . The average and median *Hipparcos* position uncertainties are slightly

TABLE 2
RADIO STAR POSITIONS ESTIMATED FROM THE VLA+PT DATA

| Star Name | Hipparcos Number | α (J2000.0) ^a | δ (J2000.0) | Epoch | N_{obs} ^b |
|------------------------------|------------------|---|---------------------------|-----------|-------------------------------|
| UV Psc..... | 5980 | 01 16 55.1402 \pm 0.0012 (\pm 0.018) | 06 48 42.242 \pm 0.020 | 2003.6933 | 1/5 |
| HD 8357..... | 6454 | 01 22 56.7799 \pm 0.0003 (\pm 0.004) | 07 25 10.126 \pm 0.006 | 2003.4356 | 6/6 |
| RZ Cas..... | 13133 | 02 48 55.5126 \pm 0.0015 (\pm 0.008) | 69 38 03.563 \pm 0.010 | 2003.4356 | 5/6 |
| B Per..... | 20070 | 04 18 14.6323 \pm 0.0005 (\pm 0.005) | 50 17 43.617 \pm 0.004 | 2003.4356 | 6/7 |
| HD 283572..... | 20388 | 04 21 58.8519 \pm 0.0015 (\pm 0.019) | 28 18 06.379 \pm 0.019 | 2003.6933 | 3/5 |
| T Tau N..... | 20390 | 04 21 59.4364 \pm 0.0007 (\pm 0.009) | 19 32 06.394 \pm 0.011 | 2003.6933 | 5/5 |
| HD 37017..... | 26233 | 05 35 21.8672 \pm 0.0006 (\pm 0.009) | -04 29 39.013 \pm 0.009 | 2003.6933 | 6/7 |
| ϵ Ori..... | 26311 | 05 36 12.8130 \pm 0.0005 (\pm 0.007) | -01 12 06.924 \pm 0.012 | 2003.4356 | 6/7 |
| α Ori..... | 27989 | 05 55 10.3097 \pm 0.0004 (\pm 0.005) | 07 24 25.461 \pm 0.012 | 2003.4356 | 7/7 |
| SV Cam..... | 32015 | 06 41 19.1451 \pm 0.0061 (\pm 0.012) | 82 16 01.905 \pm 0.012 | 2003.4356 | 1/7 |
| HD 50896..... | 33165 | 06 54 13.0405 \pm 0.0023 (\pm 0.032) | -23 55 42.023 \pm 0.025 | 2003.6933 | 3/6 |
| R CMa..... | 35487 | 07 19 28.2380 \pm 0.0003 (\pm 0.004) | -16 23 43.564 \pm 0.007 | 2004.8000 | 3/5 |
| 54 Cam..... | 39348 | 08 02 35.7663 \pm 0.0004 (\pm 0.003) | 57 16 24.834 \pm 0.007 | 2003.6933 | 5/6 |
| TY Pyx..... | 44164 | 08 59 42.7071 \pm 0.0008 (\pm 0.011) | -27 48 58.911 \pm 0.012 | 2004.8000 | 3/5 |
| XY UMa..... | 44998 | 09 09 55.9135 \pm 0.0029 (\pm 0.025) | 54 29 17.044 \pm 0.019 | 2003.6933 | 3/6 |
| IL Hya..... | 46159 | 09 24 49.0001 \pm 0.0006 (\pm 0.008) | -23 49 34.859 \pm 0.023 | 2004.8000 | 5/6 |
| DH Leo..... | 49018 | 10 00 01.6464 \pm 0.0008 (\pm 0.011) | 24 33 09.822 \pm 0.014 | 2003.6933 | 3/5 |
| HU Vir..... | 59600 | 12 13 20.6889 \pm 0.0007 (\pm 0.010) | -09 04 46.862 \pm 0.016 | 2004.8000 | 4/6 |
| DK Dra..... | 59796 | 12 15 41.4825 \pm 0.0032 (\pm 0.014) | 72 33 04.221 \pm 0.009 | 2003.6933 | 5/6 |
| RS CVn..... | 64293 | 13 10 36.8927 \pm 0.0005 (\pm 0.006) | 35 56 05.658 \pm 0.005 | 2003.4356 | 7/8 |
| HR 5110..... | 66257 | 13 34 47.8330 \pm 0.0006 (\pm 0.007) | 37 10 56.655 \pm 0.003 | 2003.6933 | 4/5 |
| RV Lib..... | 71380 | 14 35 48.4130 \pm 0.0005 (\pm 0.008) | -18 02 11.598 \pm 0.011 | 2003.4356 | 5/5 |
| δ Lib..... | 73473 | 15 00 58.3328 \pm 0.0005 (\pm 0.007) | -08 31 08.248 \pm 0.011 | 2003.6933 | 3/6 |
| AG Dra..... | 78512 | 16 01 41.0080 \pm 0.0030 (\pm 0.018) | 66 48 10.110 \pm 0.021 | 2003.4356 | 7/8 |
| σ^2 CrB..... | 79607 | 16 14 40.7704 \pm 0.0007 (\pm 0.009) | 33 51 30.688 \pm 0.005 | 2003.6933 | 4/4 |
| α Sco..... | 80763 | 16 29 24.4568 \pm 0.0005 (\pm 0.007) | -26 25 55.286 \pm 0.014 | 2003.4356 | 5/5 |
| WW Dra..... | 81519 | 16 39 03.9889 \pm 0.0014 (\pm 0.010) | 60 41 58.551 \pm 0.013 | 2003.6933 | 6/7 |
| 29 Dra..... | 85852 | 17 32 41.1473 \pm 0.0033 (\pm 0.013) | 74 13 38.567 \pm 0.015 | 2003.6933 | 7/7 |
| Z Her..... | 87965 | 17 58 06.9733 \pm 0.0009 (\pm 0.013) | 15 08 22.179 \pm 0.013 | 2003.4356 | 6/6 |
| 9 Sgr..... | 88469 | 18 03 52.4445 \pm 0.0009 (\pm 0.012) | -24 21 38.651 \pm 0.022 | 2003.6933 | 4/5 |
| FR Sct..... | 90115 | 18 23 22.7919 \pm 0.0008 (\pm 0.011) | -12 40 51.833 \pm 0.017 | 2003.4356 | 3/5 |
| BY Dra..... | 91009 | 18 33 55.8399 \pm 0.0013 (\pm 0.012) | 51 43 07.724 \pm 0.014 | 2003.6933 | 7/7 |
| HR 7275..... | 94013 | 19 08 25.7296 \pm 0.0016 (\pm 0.014) | 52 25 32.351 \pm 0.016 | 2004.8000 | 1/6 |
| U Sge..... | 94910 | 19 18 48.4085 \pm 0.0002 (\pm 0.003) | 19 36 37.724 \pm 0.004 | 2003.4356 | 6/6 |
| V444 Cyg..... | 100214 | 20 19 32.4209 \pm 0.0010 (\pm 0.011) | 38 43 53.954 \pm 0.008 | 2003.6933 | 4/6 |
| HD 193793 ^c | 100287 | 20 20 27.9752 \pm 0.0004 (\pm 0.004) | 43 51 16.271 \pm 0.002 | 2003.4356 | 5/6 |
| HD 193793..... | 100287 | 20 20 27.9747 \pm 0.0004 (\pm 0.004) | 43 51 16.268 \pm 0.003 | 2004.8000 | 4/4 |
| V729 Cyg..... | 101341 | 20 32 22.4221 \pm 0.0008 (\pm 0.009) | 41 18 18.919 \pm 0.011 | 2003.6933 | 5/5 |
| HD 199178..... | 103144 | 20 53 53.6634 \pm 0.0014 (\pm 0.015) | 44 23 11.089 \pm 0.009 | 2003.4356 | 6/6 |
| ER Vul..... | 103833 | 21 02 25.9309 \pm 0.0013 (\pm 0.018) | 27 48 26.485 \pm 0.017 | 2003.6933 | 6/6 |
| VV Cep..... | 108317 | 21 56 39.1425 \pm 0.0019 (\pm 0.013) | 63 37 31.997 \pm 0.011 | 2003.4356 | 7/7 |
| RT Lac..... | 108728 | 22 01 30.7601 \pm 0.0019 (\pm 0.021) | 43 53 25.734 \pm 0.012 | 2003.6933 | 7/7 |
| AR Lac..... | 109303 | 22 08 40.8027 \pm 0.0003 (\pm 0.003) | 45 44 32.281 \pm 0.004 | 2003.4356 | 8/8 |
| IM Peg..... | 112997 | 22 53 02.2589 \pm 0.0002 (\pm 0.003) | 16 50 28.168 \pm 0.003 | 2004.8000 | 6/6 |
| SZ Psc..... | 114639 | 23 13 23.7901 \pm 0.0001 (\pm 0.001) | 02 40 31.689 \pm 0.004 | 2003.4356 | 6/6 |
| λ And..... | 116584 | 23 37 33.8999 \pm 0.0009 (\pm 0.010) | 46 27 27.808 \pm 0.007 | 2003.6933 | 6/6 |
| HD 224085..... | 117915 | 23 55 04.2039 \pm 0.0004 (\pm 0.005) | 28 38 01.356 \pm 0.018 | 2003.4356 | 7/7 |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Second error (in parentheses) is in arcseconds.

^b Number of successful/total observations (scans).

^c HD 193793 was observed in experiments AF399a and AJ315.

larger in $\alpha \cos \delta$ at 12.0 and 10.3 mas, respectively, and slightly smaller in δ at 10.3 and 8.8 mas, respectively.

Listed in columns (9) and (10) of Table 3 are the offsets between our VLA+PT positions and the *Hipparcos* positions updated to the epoch of our observations. These offsets, $\Delta_{\text{Hipp.}-\text{radio}}$, are also shown as a function of right ascension in Figure 2 and as a function of declination in Figure 3. Stars observed in the three different experiments are represented by different symbols. Error bars are the combined uncertainties reported in columns (7) and (8) of Table 3. The unweighted mean offsets between our positions and the updated *Hipparcos* positions are 6.1 mas in $\Delta\alpha \cos \delta$ and

0.7 mas in $\Delta\delta$, with standard deviations (σ) of 18.6 and 25.1 mas in $\Delta\alpha \cos \delta$ and $\Delta\delta$, respectively. Unweighted standard errors of the means (σ_M) are then 2.7 mas in $\Delta\alpha \cos \delta$ and 3.7 mas in $\Delta\delta$. Similarly, the mean offsets between the VLA+PT and *Hipparcos* positions, weighted by the square of the rss combined uncertainties, are 2.3 and -0.7 mas with weighted rms errors of 14.3 and 17.4 mas in $\Delta\alpha \cos \delta$ and $\Delta\delta$, respectively.

The unweighted average and median arc length between our measurements and the *Hipparcos* positions is 24.2 and 15.7 mas, respectively, with a standard deviation of 20.5 mas. There are two stars for which the arc length is greater than 75 mas: DH Leo

TABLE 3
RADIO STAR POSITION UNCERTAINTIES AND OFFSETS FROM *Hipparcos*

| STAR NAME (1) | Hipparcos NUMBER (2) | RADIO ERRORS (mas) | | Hipparcos ERRORS ^a (mas) | | COMBINED ERRORS ^b (mas) | | $\Delta_{\text{Hipp.}-\text{radio}}$ (mas) | |
|---------------------|----------------------------|-----------------------------|-----------------|--|-----------------|---------------------------------------|-----------------|---|------------------|
| | | $\alpha \cos \delta$ (3) | δ (4) | $\alpha \cos \delta$ (5) | δ (6) | $\alpha \cos \delta$ (7) | δ (8) | $\alpha \cos \delta$ (9) | δ (10) |
| UV Psc..... | 5980 | 17.8 | 20.3 | 13.9 | 11.2 | 22.6 | 23.2 | 6.6 | -51.4 |
| HD 8357..... | 6454 | 4.4 | 5.8 | 12.0 | 8.1 | 12.7 | 10.0 | 2.2 | 7.4 |
| RZ Cas..... | 13133 | 8.0 | 10.1 | 5.0 | 6.8 | 9.5 | 12.2 | 7.0 | -1.3 |
| B Per..... | 20070 | 5.1 | 4.4 | 14.3 | 11.5 | 15.2 | 12.3 | 25.1 | -7.5 |
| HD 283572..... | 20388 | 18.7 | 19.5 | 19.2 | 13.9 | 26.8 | 23.9 | -22.8 | 23.2 |
| T Tau N..... | 20390 | 10.0 | 11.0 | 23.0 | 19.8 | 25.0 | 22.6 | 35.2 | -10.9 |
| HD 37017..... | 26233 | 9.2 | 9.4 | 10.6 | 6.9 | 14.0 | 11.6 | 3.3 | -3.6 |
| ϵ Ori..... | 26311 | 6.9 | 12.1 | 9.8 | 5.4 | 12.0 | 13.3 | 12.1 | 10.0 |
| α Ori..... | 27989 | 5.3 | 12.0 | 28.1 | 17.8 | 28.5 | 21.5 | 26.5 | 4.3 |
| SV Cam..... | 32015 | 12.4 | 12.1 | 11.6 | 14.3 | 16.9 | 18.7 | -5.1 | -19.2 |
| HD 50896..... | 33165 | 32.2 | 25.4 | 5.3 | 8.1 | 32.6 | 26.7 | 35.9 | 29.8 |
| R CMa..... | 35487 | 3.6 | 6.6 | 9.4 | 9.6 | 10.0 | 11.7 | 8.3 | 26.3 |
| 54 Cam..... | 39348 | 2.8 | 6.7 | 9.5 | 7.7 | 9.9 | 10.2 | -9.2 | 1.7 |
| TY Pyx..... | 44164 | 10.6 | 12.3 | 6.4 | 7.5 | 12.3 | 14.4 | 2.8 | 3.6 |
| XY UMa..... | 44998 | 25.9 | 19.1 | 21.1 | 14.4 | 33.5 | 23.9 | 34.6 | -27.7 |
| IL Hya..... | 46159 | 8.4 | 23.2 | 9.9 | 7.5 | 13.0 | 24.4 | 34.2 | -11.2 |
| DH Leo..... | 49018 | 11.2 | 13.6 | 13.7 | 10.0 | 17.7 | 16.9 | -49.5 | -95.6 |
| HU Vir..... | 59600 | 9.7 | 16.2 | 13.4 | 9.8 | 16.6 | 18.9 | 22.4 | -20.9 |
| DK Dra..... | 59796 | 8.5 | 9.1 | 6.8 | 6.2 | 10.9 | 11.0 | 0.0 | -12.7 |
| RS CVn..... | 64293 | 6.1 | 4.9 | 10.7 | 8.8 | 12.3 | 10.1 | 13.7 | 12.0 |
| HR 5110..... | 66257 | 6.9 | 3.0 | 5.5 | 4.8 | 8.8 | 5.6 | 5.4 | -6.9 |
| RV Lib..... | 71380 | 7.6 | 11.3 | 21.5 | 17.3 | 22.8 | 20.7 | 4.8 | -3.8 |
| δ Lib..... | 73473 | 8.6 | 10.7 | 10.5 | 9.9 | 13.6 | 14.6 | -18.5 | 41.5 |
| AG Dra..... | 78512 | 17.9 | 21.0 | 11.2 | 13.2 | 21.2 | 24.8 | 11.3 | 10.3 |
| σ^2 CrB..... | 79607 | 8.7 | 4.8 | 10.5 | 13.7 | 13.7 | 14.5 | 9.0 | -4.6 |
| α Sco..... | 80763 | 7.2 | 13.9 | 24.4 | 16.4 | 25.5 | 21.5 | 19.6 | -3.2 |
| WW Dra..... | 81519 | 10.0 | 12.6 | 18.9 | 18.9 | 21.4 | 22.8 | 34.2 | 18.6 |
| 29 Dra..... | 85852 | 13.0 | 15.2 | 10.6 | 11.5 | 16.8 | 19.1 | -20.3 | 48.2 |
| Z Her..... | 87965 | 13.0 | 13.0 | 8.4 | 7.8 | 15.5 | 15.1 | 19.5 | -20.7 |
| 9 Sgr..... | 88469 | 12.5 | 21.6 | 14.7 | 8.8 | 19.3 | 23.3 | 7.2 | 16.7 |
| FR Sct..... | 90115 | 11.0 | 17.0 | 19.8 | 14.1 | 22.6 | 22.0 | -23.0 | 74.1 |
| BY Dra..... | 91009 | 12.5 | 13.6 | 8.7 | 9.4 | 15.2 | 16.6 | 7.7 | 3.2 |
| HR 7275..... | 94013 | 14.5 | 16.0 | 6.7 | 6.4 | 15.9 | 17.3 | 44.4 | 12.7 |
| U Sge..... | 94910 | 2.9 | 3.6 | 6.6 | 7.1 | 7.2 | 8.0 | -5.1 | -4.6 |
| V444 Cyg..... | 100214 | 13.1 | 8.1 | 8.4 | 8.4 | 15.6 | 11.7 | -6.0 | -4.0 |
| HD 193793..... | 100287 | 3.9 | 2.6 | 7.1 | 6.0 | 8.1 | 6.5 | -14.3 | -4.6 |
| HD 193793..... | 100287 | 4.1 | 2.3 | 7.9 | 6.7 | 8.9 | 7.0 | -10.4 | -4.9 |
| V729 Cyg..... | 101341 | 8.7 | 10.9 | 33.6 | 29.5 | 34.7 | 31.4 | 26.4 | 29.8 |
| HD 199178..... | 103144 | 14.8 | 8.8 | 9.4 | 7.5 | 17.5 | 11.5 | -18.7 | -8.1 |
| ER Vul..... | 103833 | 17.6 | 17.4 | 7.0 | 7.0 | 19.0 | 18.8 | 8.1 | -12.7 |
| VV Cep..... | 108317 | 12.8 | 10.7 | 7.7 | 5.6 | 15.0 | 12.1 | 7.5 | -3.9 |
| RT Lac..... | 108728 | 20.8 | 12.0 | 10.3 | 11.0 | 23.2 | 16.3 | 1.1 | -11.5 |
| AR Lac..... | 109303 | 3.0 | 4.0 | 5.6 | 6.5 | 6.4 | 7.6 | 2.0 | 9.1 |
| IM Peg..... | 112997 | 3.4 | 3.3 | 8.3 | 7.7 | 8.9 | 8.4 | -5.6 | -1.6 |
| SZ Psc..... | 114639 | 1.4 | 4.3 | 14.9 | 9.9 | 15.0 | 10.8 | 5.4 | -12.8 |
| λ And..... | 116584 | 9.5 | 6.5 | 4.0 | 6.2 | 10.3 | 9.0 | -1.2 | 14.0 |
| HD 224085..... | 117915 | 4.6 | 17.6 | 9.7 | 6.8 | 10.7 | 18.9 | 13.2 | 5.9 |

^a *Hipparcos* uncertainties updated to the epoch of our observations using the *Hipparcos* proper-motion uncertainties.

^b Combined uncertainties are the rss of our VLA+PT errors and the corresponding *Hipparcos* errors at epoch.

(HIP 49018) and FR Sct (HIP 90115). For both stars the declination offset is the dominant source of the difference from *Hipparcos*; however, neither source has an unusually large uncertainty in declination, 13.6 mas for DH Leo and 17.0 mas for FR Sct. In addition, neither source has a particularly large proper motion in declination, -31.8 and -2.9 mas yr $^{-1}$ for DH Leo and FR Sct, respectively.

DH Leo is an RS CVn binary, as are many of the radio stars on our list. The system is flagged as a component solution in the

Hipparcos Double/Multiple Systems Annex (Perryman et al. 1997). The annex lists a tertiary component with a separation of 220 ± 20 mas with respect to DH Leo at a position angle of 46° at epoch 1991.25. DH Leo is also listed in the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2001) as multiple system CHARA 145. The catalog lists eight measurements of the component separations made with speckle interferometry from epoch 1989.2271 through 1994.2209. Over this 5 yr period the components moved through angles from 38°

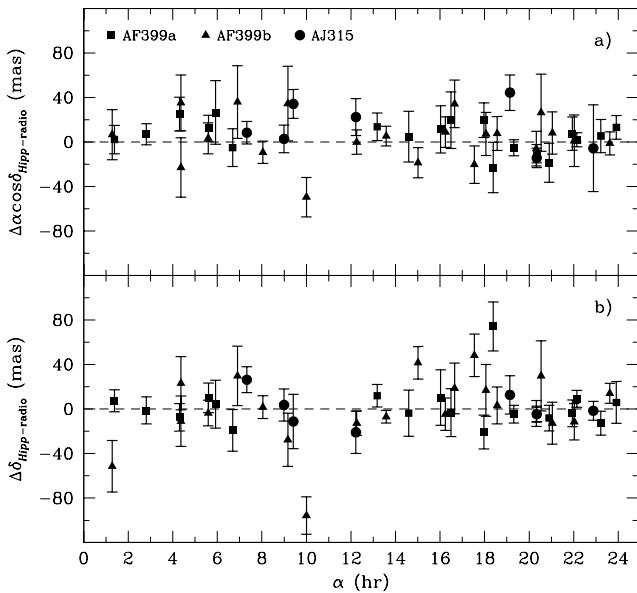


FIG. 2.—Differences between the *Hipparcos* positions updated to the epoch of our observations and our VLA+PT measured positions as a function of source right ascension α for the 46 radio stars observed. Differences in $\alpha \cos \delta$ are plotted in (a), and differences in δ are plotted in (b). Error bars are the rss combined uncertainties listed in Table 3.

to 28° and relative separations of 216–283 mas. It is therefore possible that the 96 mas offset in declination between our radio position and the *Hipparcos* position updated to our epoch is consistent with the orbital motion within the system.

FR Sct, on the other hand, is a single pulsating variable star. The *Hipparcos* Catalogue solution contains no entry in the Double/Multiple Systems Annex (Perryman et al. 1997). In addition, there are no entries for FR Sct in the Washington Double Star Catalog (Mason et al. 2001) or the Fourth Catalog of Interferometric Measurements of Binary Stars (Hartkopf et al. 2001). Therefore, the 74 mas offset in declination between our radio position and the corresponding *Hipparcos* position cannot, as yet, be explained as motion due to a secondary component. It may be that FR Sct is a good candidate for future speckle interferometry observations in light of the offset we have found.

3.2. Source Proper Motions

The positions of the 46 radio stars from our VLA+PT observations were combined with previous VLA (Johnston et al. 1985, 2003), VLA+PT (Boboltz et al. 2003), and MERLIN (Fey et al. 2006) positions to determine updated proper motions, $\mu_{\alpha \cos \delta}$ and μ_δ , for all 46 sources. Although the data cover a long time range, 1978–2004, the sampling is not sufficient to enable the determination of source parallaxes. We therefore used the *Hipparcos* values to remove the effects of parallax in our computed proper motions for all 46 stars. Source proper motions were computed using a linear least-squares fit to the data weighted by the position errors for each observation. Position errors for the previous VLA-only observations were estimated to be 30 mas in both $\alpha \cos \delta$ and δ (Johnston et al. 2003), and we have adopted these values. Position errors for previous VLA+PT and MERLIN observations are reported in Boboltz et al. (2003) and Fey et al. (2006), respectively. The proper motions derived from the combined data are listed in Table 4. Also reported are the number of positions used to determine the proper motion (N_{pos}) and the total time span between the earliest position measurement and the most recent measurement ($\Delta\tau$). There are three stars, T Tau N (HIP 20390), HD 199178 (HIP 100287),

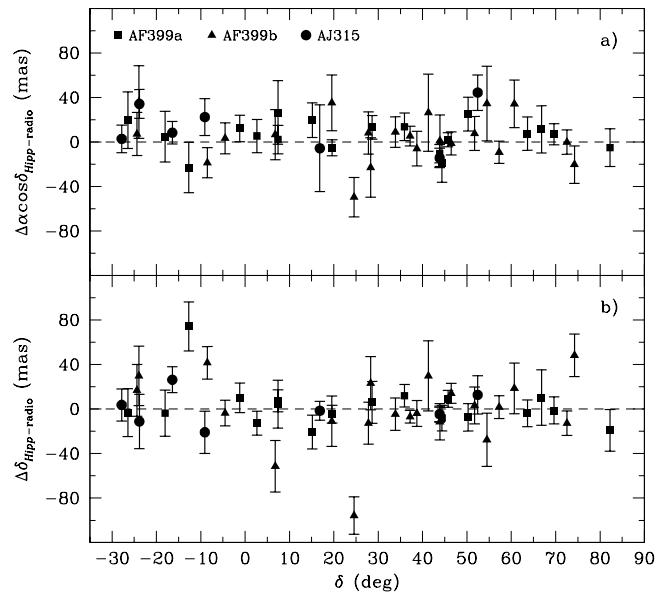


FIG. 3.—Differences between the *Hipparcos* positions updated to the epoch of our observations and our VLA+PT measured positions as a function of source declination δ for the 46 radio stars observed. Differences in $\alpha \cos \delta$ are plotted in (a), and differences in δ are plotted in (b). Error bars are the rss combined uncertainties listed in Table 3.

and IM Peg (HIP 112997), for which the time baseline is short, $\Delta\tau < 4$ yr. These three stars are recent additions to our observing list and were not part of the original VLA radio star program (Johnston et al. 1985, 2003).

Table 5 compares the uncertainties in our radio-derived proper motions with the corresponding *Hipparcos* proper-motion uncertainties and lists the rss combined uncertainties for each star. Listed in columns (9) and (10) of Table 5 are the differences between our VLA+PT proper motions and the corresponding *Hipparcos* values. These differences are also shown in Figures 4–8. Figures 4 and 5 show the proper-motion differences $\Delta\mu_{\alpha \cos \delta}$ and $\Delta\mu_\delta$ as a function of right ascension (Fig. 4) and declination (Fig. 5), respectively. The three different symbols represent stars observed in the three corresponding VLA+PT experiments. Error bars are the combined uncertainties reported in columns (7) and (8) of Table 5. Average and median radio-derived uncertainties for the 46 stars are 1.74 and 1.62 mas yr $^{-1}$, respectively, in $\mu_{\alpha \cos \delta}$ and 1.79 and 1.65 mas yr $^{-1}$, respectively, in μ_δ . If we exclude the three stars for which $\Delta\tau < 4$ yr, these values drop slightly to 1.59 and 1.62 mas yr $^{-1}$ in $\mu_{\alpha \cos \delta}$ and 1.62 and 1.64 mas yr $^{-1}$ in μ_δ . For comparison, the average *Hipparcos* proper-motion uncertainties are 0.98 and 0.85 mas yr $^{-1}$ in $\mu_{\alpha \cos \delta}$ and 0.84 and 0.72 mas yr $^{-1}$ in μ_δ for the same 46 stars.

The unweighted average differences between our proper motions and the *Hipparcos* values are -0.75 mas yr $^{-1}$ in $\Delta\mu_{\alpha \cos \delta}$ and 0.21 mas yr $^{-1}$ in $\Delta\mu_\delta$, with standard deviations of 2.17 and 2.38 mas yr $^{-1}$ in $\Delta\mu_{\alpha \cos \delta}$ and $\Delta\mu_\delta$, respectively. Unweighted standard errors of the means (σ_M) are thus 0.35 mas yr $^{-1}$ in $\Delta\mu_{\alpha \cos \delta}$ and 0.32 mas yr $^{-1}$ in $\Delta\mu_\delta$. Similarly, the mean offsets between the radio and *Hipparcos* proper motions, weighted by the square of the rss combined uncertainties, are -0.57 and -0.15 mas yr $^{-1}$ with weighted rms errors of 1.77 and 2.26 mas yr $^{-1}$ in $\Delta\mu_{\alpha \cos \delta}$ and $\Delta\mu_\delta$, respectively.

Figures 6, 7, and 8 plot the differences, $\Delta\mu_\delta$ versus $\Delta\mu_{\alpha \cos \delta}$, for the experiments AF399a, AF399b, and AJ315, respectively. Again, the error bars represent the rss combined uncertainties. The figures show that many of the differences between the radio proper motions and those of *Hipparcos* are within the 1σ error

TABLE 4
RADIO STAR PROPER MOTIONS

| Star Name | Hipparcos Number | $\mu_{\alpha \cos \delta}$ (mas yr $^{-1}$) | μ_{δ} (mas yr $^{-1}$) | $N_{\text{pos}}^{\text{a}}$ | $\Delta\tau^{\text{b}}$ (yr) |
|---------------------|------------------|---|-------------------------------------|-----------------------------|---------------------------------|
| UV Psc..... | 5980 | 84.87 \pm 2.36 | 23.62 \pm 2.45 | 2 | 14.6893 |
| HD 8357..... | 6454 | 96.17 \pm 1.17 | 234.07 \pm 1.20 | 3 | 18.3986 |
| RZ Cas..... | 13133 | 3.20 \pm 1.51 | 36.55 \pm 1.60 | 5 | 17.1376 |
| B Per..... | 20070 | 43.64 \pm 1.22 | -58.02 \pm 1.21 | 7 | 21.0065 |
| HD 283572..... | 20388 | 9.98 \pm 1.94 | -29.00 \pm 1.90 | 2 | 18.6563 |
| T Tau N..... | 20390 | 7.20 \pm 4.15 | -4.84 \pm 5.17 | 2 | 2.7484 |
| HD 37017..... | 26233 | 1.07 \pm 1.51 | 2.63 \pm 1.51 | 4 | 18.6563 |
| ϵ Ori..... | 26311 | -2.12 \pm 1.66 | -0.91 \pm 1.78 | 3 | 17.2176 |
| α Ori..... | 27989 | 23.98 \pm 1.04 | 10.07 \pm 1.15 | 4 | 21.0175 |
| SV Cam..... | 32015 | 41.99 \pm 1.90 | -150.02 \pm 1.81 | 2 | 17.1376 |
| HD 50896..... | 33165 | -3.70 \pm 2.06 | 6.58 \pm 1.94 | 3 | 20.0172 |
| R CMa..... | 35487 | 166.19 \pm 1.64 | -139.38 \pm 1.66 | 2 | 18.5820 |
| 54 Cam..... | 39348 | -38.80 \pm 1.24 | -56.95 \pm 1.39 | 4 | 21.2672 |
| TY Pyx..... | 44164 | -45.68 \pm 1.49 | -46.24 \pm 1.52 | 3 | 21.1239 |
| XY UMa..... | 44998 | -50.19 \pm 2.24 | -182.06 \pm 2.04 | 2 | 17.3953 |
| IL Hya..... | 46159 | -42.65 \pm 1.98 | -30.58 \pm 2.39 | 2 | 15.7960 |
| DH Leo..... | 49018 | -231.88 \pm 1.71 | -31.78 \pm 1.77 | 2 | 18.6583 |
| HU Vir..... | 59600 | -13.22 \pm 1.99 | 1.33 \pm 2.15 | 2 | 15.7960 |
| DK Dra..... | 58796 | -9.55 \pm 1.79 | -23.80 \pm 1.68 | 2 | 18.6583 |
| RS CVn..... | 64293 | -50.53 \pm 1.39 | 23.17 \pm 1.28 | 4 | 21.0145 |
| HR 5110..... | 66257 | 85.40 \pm 1.07 | -9.06 \pm 0.99 | 5 | 21.2752 |
| RV Lib..... | 71380 | -20.71 \pm 1.79 | -18.24 \pm 1.86 | 2 | 17.2176 |
| δ Lib..... | 73473 | -66.16 \pm 1.51 | -6.19 \pm 1.62 | 6 | 17.4753 |
| AG Dra..... | 78512 | -9.68 \pm 2.03 | -7.61 \pm 2.13 | 2 | 17.2176 |
| σ^2 CrB..... | 79607 | -267.19 \pm 1.31 | -86.86 \pm 1.22 | 4 | 21.2752 |
| α Sco..... | 80763 | -10.06 \pm 1.07 | -23.81 \pm 1.24 | 3 | 21.0175 |
| WW Dra..... | 81519 | 22.16 \pm 1.26 | -60.40 \pm 1.32 | 3 | 20.0172 |
| 29 Dra..... | 85852 | -66.85 \pm 1.89 | 33.88 \pm 1.92 | 2 | 17.4753 |
| Z Her..... | 87965 | -26.82 \pm 1.67 | 77.48 \pm 1.65 | 2 | 19.7596 |
| 9 Sgr..... | 88469 | 0.48 \pm 1.62 | -3.94 \pm 1.85 | 2 | 20.0642 |
| FR Sct..... | 90115 | 0.00 \pm 1.66 | -2.88 \pm 1.74 | 2 | 19.8065 |
| BY Dra..... | 91009 | 186.49 \pm 1.60 | -325.12 \pm 1.65 | 2 | 20.0172 |
| HR 7275..... | 94013 | -102.73 \pm 1.81 | -55.05 \pm 1.83 | 2 | 18.5820 |
| U Sge..... | 94910 | 0.62 \pm 1.62 | 2.50 \pm 1.64 | 2 | 18.3986 |
| V444 Cyg..... | 100214 | -5.67 \pm 1.22 | -7.62 \pm 1.13 | 3 | 20.0172 |
| HD 193793..... | 100287 | -4.72 \pm 0.66 | -1.89 \pm 0.64 | 9 | 22.3819 |
| V729 Cyg..... | 101341 | -2.79 \pm 1.44 | -5.35 \pm 1.48 | 4 | 20.0642 |
| HD 199178..... | 103144 | 27.12 \pm 6.14 | -1.03 \pm 3.51 | 3 | 2.4907 |
| ER Vul..... | 103833 | 89.78 \pm 2.39 | 5.24 \pm 2.35 | 2 | 14.6893 |
| VV Cep..... | 108317 | -4.95 \pm 1.64 | -2.27 \pm 1.61 | 2 | 19.8065 |
| RT Lac..... | 108728 | 57.54 \pm 1.72 | 20.69 \pm 1.52 | 2 | 21.2672 |
| AR Lac..... | 109303 | -52.43 \pm 1.02 | 46.77 \pm 1.07 | 7 | 21.0095 |
| IM Peg..... | 112997 | -18.62 \pm 1.34 | -27.76 \pm 4.22 | 2 | 3.8551 |
| SZ Psc..... | 114639 | 18.64 \pm 1.41 | 27.60 \pm 1.43 | 3 | 19.8065 |
| λ And..... | 116584 | 158.77 \pm 1.47 | -423.50 \pm 1.45 | 2 | 21.2752 |
| HD 224085..... | 117915 | 576.20 \pm 1.45 | 34.27 \pm 1.67 | 2 | 21.0095 |

^a Number of position measurements used in the weighted least-squares fit to estimate the proper motion.

^b Time in years between first and last position epochs.

bars, with the most obvious exception being the star T Tau N in Figure 7. As mentioned previously, T Tau N is one of the stars for which the time baseline is short at only 2.75 yr. In addition, T Tau N is known to be gravitationally bound to the T Tau S binary system with a detected acceleration in its motion (Johnston et al. 2004). With only two positions for T Tau N covering such a short time period it is impossible to fit for any accelerations in the motion of the source with our data alone.

The two stars mentioned previously as having large declination differences relative to *Hipparcos*, FR Sct and DH Leo, appear in Figures 6 and 7, respectively. Although the proper motions in declination (see Table 4) are not very large, the proper-motion differences in declination relative to *Hipparcos* are fairly large at

-3.35 mas yr $^{-1}$ for FR Sct and 4.33 mas yr $^{-1}$ for DH Leo. Table 4 shows that both stars have only two position measurements separated by long time intervals between epochs. It is possible that the two stars have an acceleration component in declination that is as yet undetected in the linear fits to our limited data.

3.3. Radio/Optical Frame Alignment

Our radio star observations are on the ICRF, while the data taken from the *Hipparcos* Catalogue are on the *Hipparcos* Celestial Reference Frame (HCRF). The *Hipparcos* positions used here have been updated to the epoch of the individual radio star's mean position using the *Hipparcos* proper motions. Following the formulation of Walter & Sovers (2000), the optical minus radio

TABLE 5
RADIO STAR PROPER-MOTION UNCERTAINTIES AND OFFSETS FROM *Hipparcos*

| STAR NAME (1) | Hipparcos NUMBER (2) | RADIO ERRORS (mas) | | Hipparcos ERRORS (mas) | | COMBINED ERRORS ^a (mas) | | $\Delta\mu_{\text{Hipp.}-\text{radio}}$ (mas) | |
|---------------------|-------------------------|-----------------------------------|-----------------------|-----------------------------------|-----------------------|---------------------------------------|-----------------------|--|------------------------|
| | | $\mu_{\alpha \cos \delta}$ (3) | μ_{δ} (4) | $\mu_{\alpha \cos \delta}$ (5) | μ_{δ} (6) | $\mu_{\alpha \cos \delta}$ (7) | μ_{δ} (8) | $\mu_{\alpha \cos \delta}$ (9) | μ_{δ} (10) |
| UV Psc..... | 5980 | 2.36 | 2.45 | 1.14 | 0.92 | 2.63 | 2.62 | 0.03 | 4.39 |
| HD 8357..... | 6454 | 1.17 | 1.20 | 0.98 | 0.66 | 1.53 | 1.37 | 1.78 | 3.34 |
| RZ Cas..... | 13133 | 1.51 | 1.60 | 0.41 | 0.56 | 1.56 | 1.69 | 0.31 | -0.92 |
| B Per..... | 20070 | 1.22 | 1.21 | 1.17 | 0.94 | 1.69 | 1.53 | -2.95 | -1.59 |
| HD 283572..... | 20388 | 1.94 | 1.90 | 1.57 | 1.14 | 2.50 | 2.22 | 2.46 | -1.55 |
| T Tau N..... | 20390 | 4.15 | 5.17 | 1.88 | 1.62 | 4.55 | 5.42 | -8.25 | 7.64 |
| HD 37017..... | 26233 | 1.51 | 1.51 | 0.86 | 0.56 | 1.73 | 1.61 | -1.05 | 1.69 |
| ϵ Ori..... | 26311 | 1.66 | 1.78 | 0.80 | 0.44 | 1.85 | 1.84 | -3.61 | 0.15 |
| α Ori..... | 27989 | 1.04 | 1.15 | 2.30 | 1.46 | 2.52 | 1.86 | -3.35 | -0.79 |
| SV Cam..... | 32015 | 1.90 | 1.81 | 0.95 | 1.17 | 2.12 | 2.16 | 0.41 | 2.89 |
| HD 50896..... | 33165 | 2.06 | 1.94 | 0.43 | 0.66 | 2.10 | 2.05 | 0.16 | 1.83 |
| R CMa..... | 35487 | 1.64 | 1.66 | 0.69 | 0.71 | 1.78 | 1.80 | 0.82 | -2.97 |
| 54 Cam..... | 39348 | 1.24 | 1.39 | 0.78 | 0.63 | 1.46 | 1.53 | -0.52 | 2.13 |
| TY Pyx..... | 44164 | 1.49 | 1.52 | 0.47 | 0.55 | 1.56 | 1.62 | -1.69 | -1.44 |
| XY UMa..... | 44998 | 2.24 | 2.04 | 1.73 | 1.18 | 2.83 | 2.36 | -2.11 | 2.61 |
| IL Hya..... | 46159 | 1.98 | 2.39 | 0.73 | 0.55 | 2.11 | 2.46 | -5.14 | 1.62 |
| DH Leo..... | 49018 | 1.71 | 1.77 | 1.11 | 0.81 | 2.04 | 1.95 | 2.49 | 4.33 |
| HU Vir..... | 59600 | 1.99 | 2.15 | 0.99 | 0.72 | 2.22 | 2.27 | -1.52 | 1.76 |
| DK Dra..... | 59796 | 1.79 | 1.68 | 0.56 | 0.51 | 1.88 | 1.75 | -0.35 | 1.31 |
| RS CVn..... | 64293 | 1.39 | 1.28 | 0.88 | 0.72 | 1.64 | 1.47 | -1.39 | 1.68 |
| HR 5110..... | 66257 | 1.07 | 0.99 | 0.45 | 0.39 | 1.16 | 1.06 | 0.70 | 0.75 |
| RV Lib..... | 71380 | 1.79 | 1.86 | 1.76 | 1.42 | 2.51 | 2.34 | -0.17 | 0.62 |
| δ Lib..... | 73473 | 1.51 | 1.62 | 0.86 | 0.81 | 1.74 | 1.81 | 0.04 | -2.79 |
| AG Dra..... | 78512 | 2.03 | 2.13 | 0.92 | 1.08 | 2.23 | 2.39 | -3.50 | -2.14 |
| σ^2 CrB..... | 79607 | 1.31 | 1.22 | 0.86 | 1.12 | 1.57 | 1.66 | -0.72 | 0.02 |
| α Sco..... | 80763 | 1.07 | 1.24 | 2.00 | 1.34 | 2.27 | 1.83 | 0.10 | -0.60 |
| WW Dra..... | 81519 | 1.26 | 1.32 | 1.55 | 1.55 | 2.00 | 2.04 | -2.60 | -2.03 |
| 29 Dra..... | 85852 | 1.89 | 1.92 | 0.87 | 0.94 | 2.08 | 2.14 | -0.03 | -3.19 |
| Z Her..... | 87965 | 1.67 | 1.65 | 0.69 | 0.64 | 1.81 | 1.77 | -3.19 | 3.23 |
| 9 Sgr..... | 88469 | 1.62 | 1.85 | 1.20 | 0.72 | 2.02 | 1.99 | -0.16 | -2.23 |
| FR Sct..... | 90115 | 1.66 | 1.74 | 1.62 | 1.15 | 2.32 | 2.09 | 1.76 | -3.35 |
| BY Dra..... | 91009 | 1.60 | 1.65 | 0.71 | 0.77 | 1.75 | 1.82 | -0.13 | -0.23 |
| HR 7275..... | 94013 | 1.81 | 1.83 | 0.49 | 0.47 | 1.87 | 1.89 | 1.69 | -0.78 |
| U Sge..... | 94910 | 1.62 | 1.64 | 0.54 | 0.58 | 1.71 | 1.74 | -2.32 | -0.10 |
| V444 Cyg..... | 100214 | 1.22 | 1.13 | 0.69 | 0.69 | 1.40 | 1.33 | 0.91 | 2.06 |
| HD 193793..... | 100287 | 0.66 | 0.64 | 0.58 | 0.49 | 0.88 | 0.80 | -2.00 | -4.13 |
| V729 Cyg..... | 101341 | 1.44 | 1.48 | 2.75 | 2.41 | 3.10 | 2.83 | 0.64 | 0.48 |
| HD 199178..... | 103144 | 6.14 | 3.51 | 0.77 | 0.61 | 6.19 | 3.57 | -2.11 | -2.68 |
| ER Vul..... | 103833 | 2.39 | 2.35 | 0.57 | 0.57 | 2.45 | 2.42 | 0.35 | 0.12 |
| VV Cep..... | 108317 | 1.64 | 1.61 | 0.63 | 0.46 | 1.76 | 1.68 | 1.53 | -0.86 |
| RT Lac..... | 108728 | 1.72 | 1.52 | 0.84 | 0.90 | 1.91 | 1.77 | -4.62 | 1.55 |
| AR Lac..... | 109303 | 1.02 | 1.07 | 0.46 | 0.53 | 1.12 | 1.20 | 0.23 | -0.46 |
| IM Peg..... | 112997 | 1.34 | 4.22 | 0.61 | 0.57 | 1.47 | 4.26 | 0.05 | -1.11 |
| SZ Psc..... | 114639 | 1.41 | 1.43 | 1.22 | 0.81 | 1.87 | 1.64 | 2.35 | -0.17 |
| λ And..... | 116584 | 1.47 | 1.45 | 0.33 | 0.51 | 1.51 | 1.54 | 0.53 | 1.54 |
| HD 224085..... | 117915 | 1.45 | 1.67 | 0.79 | 0.56 | 1.65 | 1.76 | -0.45 | -2.04 |

^a Combined uncertainties are the rss of our radio errors and the corresponding *Hipparcos* errors.

position differences are used to determine the relative reference frame orientation angles ϵ_x , ϵ_y , and ϵ_z around the x -, y -, and z -axes, respectively:

$$(\alpha_{\text{HCRF}} - \alpha_{\text{ICRF}}) \cos \delta = \epsilon_x \sin \delta \cos \alpha + \epsilon_y \sin \delta \sin \alpha - \epsilon_z \cos \delta, \quad (1)$$

$$\delta_{\text{HCRF}} - \delta_{\text{ICRF}} = -\epsilon_x \sin \alpha + \epsilon_y \cos \alpha. \quad (2)$$

Similar formulae are used to obtain the relative spin difference (ω_x , ω_y , and ω_z) of the reference frames using the proper-motion

differences between the *Hipparcos* Catalogue and our data. The combined rss formal errors of the *Hipparcos* and our data are used for weighted least-squares adjustments. The weighted mean epoch of our data is 2003.78, and the results, with the sign conventions from equations (1) and (2), are presented in Table 6. The first two rows of the table list the orientation (mas), spin (mas yr^{-1}), and corresponding formal errors for each axis using all 46 stars observed. The HCRF excludes stars flagged for possible multiplicity in the *Hipparcos* Catalogue. Thirteen out of the 46 radio stars we observed have a multiplicity flag in the *Hipparcos* Catalogue; thus, we have excluded them in the second solution

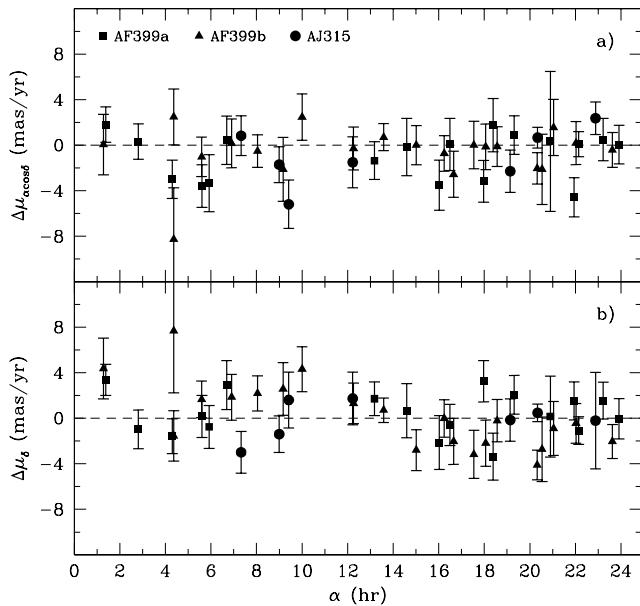


FIG. 4.—Differences between the *Hipparcos* proper motions and our radio-derived proper motions as a function of source right ascension α for the 46 radio stars observed. Differences in $\mu_{\alpha} \cos \delta$ are plotted in (a), and differences in μ_δ are plotted in (b). Error bars are the rss combined uncertainties listed in Table 5.

presented in Table 6 (labeled “33 stars”). Finally, two stars out of the remaining 33 nonmultiple stars showed large postfit residuals in the 33 star rotation solution. These stars are T Tau N, a known multiple, and RZ Cas. A third solution was produced excluding these two stars, and the results are presented in Table 6 (labeled “31 stars”).

Because ground-based catalogs often contain systematic errors, especially as a function of declination, preliminary solutions for the orientation angles included an offset in the declination parameter in addition to the three rotation terms. However, these solutions showed the offset term to be insignificant, and the results

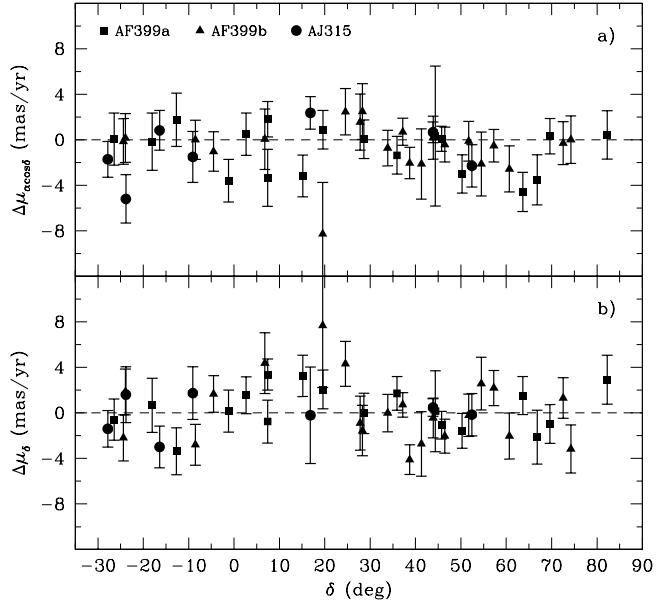


FIG. 5.—Differences between the *Hipparcos* proper motions and our radio-derived proper motions as a function of source declination δ for the 46 radio stars observed. Differences in $\mu_{\alpha} \cos \delta$ are plotted in (a), and differences in μ_δ are plotted in (b). Error bars are the rss combined uncertainties listed in Table 5.

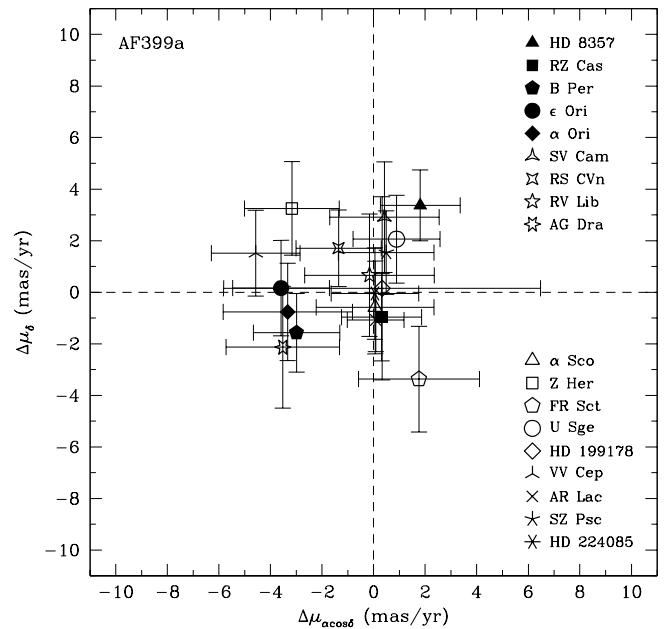


FIG. 6.—Offsets between the *Hipparcos* and radio proper motions, $\Delta \mu_{\alpha} \cos \delta$ vs. $\Delta \mu_\delta$, for the stars observed in VLA+PT experiment AF399a. Error bars are the rss combined uncertainties listed in Table 5.

presented in Table 6 are based on a model including only the three rotation terms. The reduced χ^2 was found to be 1.14 for the position orientation solution and 1.10 for the proper-motion spin solution. This is an indication of small systematic errors, and the addition of an arbitrary rss error of about 5 mas per coordinate per star will bring the χ^2 for the solutions close to 1.0. This additional error was not included in the solutions presented in Table 6.

Updating the *Hipparcos*-ICRF frame alignment discussion presented in Boboltz et al. (2003), the formal, predicted error on the frame alignment at our 2003.78 mean epoch, which is 12.53 yr after the mean *Hipparcos* epoch of 1991.25, is 3.1 mas. The

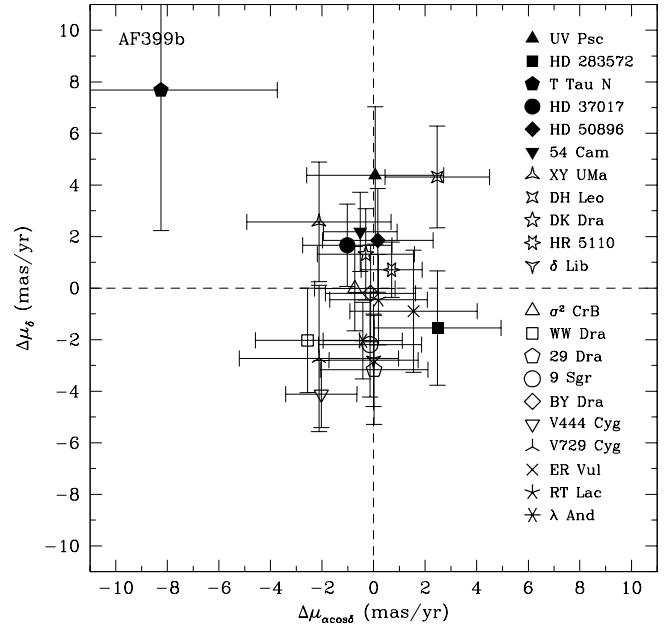


FIG. 7.—Offsets between the *Hipparcos* and radio proper motions, $\Delta \mu_{\alpha} \cos \delta$ vs. $\Delta \mu_\delta$, for the stars observed in VLA+PT experiment AF399b. Error bars are the rss combined uncertainties listed in Table 5.

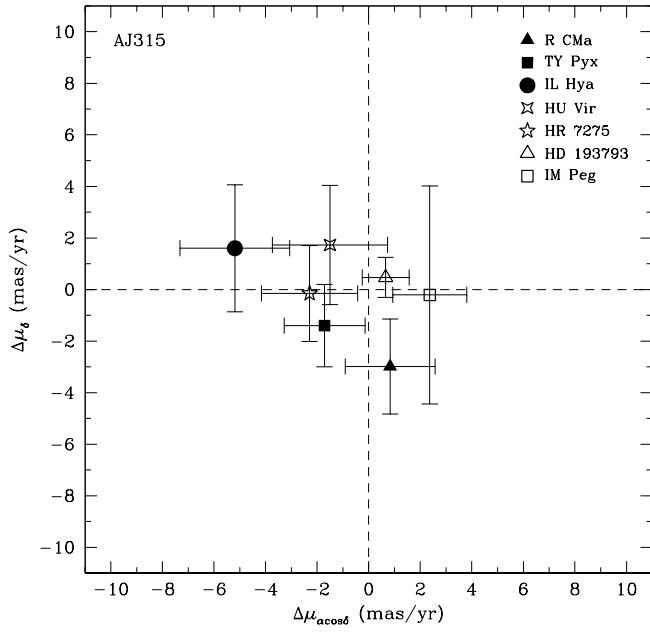


FIG. 8.—Offsets between the *Hipparcos* and radio proper motions, $\Delta\mu_{\alpha \cos\delta}$ vs. $\Delta\mu_{\delta}$, for the stars observed in VLA+PT experiment AJ315. Error bars are the rss combined uncertainties listed in Table 5.

largest frame orientation angle we find is for the z -axis with *Hipparcos*—radio = -3.2 mas, with a formal error of 2.9 mas and thus only a 1σ (non)significance. The orientations of the *Hipparcos* and ICRF frames are even better for the x - and y -axes at the 2003.78 mean epoch. For the two alternate solutions with 33 and 31 stars, the frame orientations are slightly larger for the z -axis than the 46 star solution and slightly smaller for the x - and y -axes. All rotation angles are still within the 1σ formal errors. In addition, the weighted mean offsets between the *Hipparcos* and VLA+PT positions mentioned in § 3.1 (2.3 and -0.7 mas) are consistent with the frame orientation angles and their formal errors.

With the formal errors of the *Hipparcos* data increasing over time and the radio data errors decreasing, it is now appropriate to look, for the first time, at the derivative of the frame orientation, i.e., the proper-motion spin alignment of the frames. We find formal errors in the spin alignment of only about 0.36 mas yr^{-1} per axis for the 46 star solution. This is a factor of 2 improvement over our previous results (Boboltz et al. 2003) and is approaching the original *Hipparcos*-ICRF link error of 0.25 mas yr^{-1} . Our independent observations show the *Hipparcos* frame to be non-

rotating with respect to the extragalactic ICRF, with the largest rotation rates being $+0.55$ and -0.41 mas yr^{-1} around the x - and z -axes, respectively. These rates are consistent with zero on the 1.6 and 1.1σ levels, respectively. For the 33 and 31 star solutions, the formal errors are larger at approximately 0.44 mas yr^{-1} . The rotation rate about the x -axis was nominally larger with respect to the 46 star solution at $\omega_x \approx 0.62$ mas yr^{-1} , while the rotation rate about the z -axis was slightly smaller at $\omega_z \approx -0.31$ mas yr^{-1} . All rotation rates are consistent with zero on a 1.5σ level or better. The weighted mean proper motion differences mentioned in § 3.2 (-0.57 and -0.15 mas yr^{-1}) are also consistent with these frame rotation rates and their formal errors.

4. CONCLUSIONS

We have determined the astrometric positions for 46 radio stars using the VLA+PT configuration. The positions presented here, with uncertainties on the order of 10 mas or better, are consistent with our earlier VLA+PT results (Boboltz et al. 2003) and represent a factor of 3 improvement over prior VLA-only results (Johnston et al. 1985, 2003). Stellar positions from *Hipparcos* are degrading with time due to errors in the *Hipparcos* proper motions on the order of 1 mas yr^{-1} and due to unmodeled rotations in the frame with respect to the extragalactic objects estimated to be 0.25 mas yr^{-1} per axis. Taking into account these uncertainties, for many of the stars in our list our VLA+PT positions are better than the corresponding *Hipparcos* positions at epoch. The proper motions derived from our VLA+PT positions combined with previous VLA (Johnston et al. 1985, 2003), VLA+PT (Boboltz et al. 2003), and MERLIN (Fey et al. 2006) positions have errors that are on the order of, and in some cases are better than, those obtained from *Hipparcos*.

We have also compared our radio star data with the *Hipparcos* Catalogue data for positions and proper motions and find consistency in the reference frames produced by each data set on the 1σ level. Errors of ~ 2.7 mas per axis were computed for the reference frame orientation angles at our mean epoch of 2003.78 and ~ 0.36 mas yr^{-1} per axis for relative spin between the frames. Our independent observations show the *Hipparcos* frame to be nonrotating with respect to the extragalactic ICRF, with the largest rotation rates being $+0.55$ and -0.41 mas yr^{-1} around the x - and z -axes, respectively. Future papers will reveal whether this trend has any significance. An independent study based on optical images of extragalactic reference frame sources in combination with dedicated astrograph observations is in preparation (M. I. Zacharias & N. Zacharias 2007). For now, the HCRF orientation and spin are consistent with the ICRF on the 1σ level of our observations of 46 radio stars.

TABLE 6
Hipparcos MINUS RADIO DATA REFERENCE FRAME ORIENTATION AND SPIN

| Solution | ϵ_x (mas) | ϵ_y (mas) | ϵ_z (mas) | ω_x (mas yr^{-1}) | ω_y (mas yr^{-1}) | ω_z (mas yr^{-1}) |
|-----------------------------|-----------------------|-----------------------|-----------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| All 46 stars..... | -0.4 | 0.1 | -3.2 | 0.55 | 0.02 | -0.41 |
| 1σ | 2.6 | 2.6 | 2.9 | 0.34 | 0.36 | 0.37 |
| 33 stars ^a | -1.3 | 1.2 | -2.9 | 0.61 | -0.05 | -0.32 |
| 1σ | 2.9 | 2.8 | 3.2 | 0.43 | 0.43 | 0.46 |
| 31 stars ^b | -1.7 | 0.9 | -2.4 | 0.62 | -0.01 | -0.30 |
| 1σ | 3.1 | 2.9 | 3.3 | 0.43 | 0.43 | 0.46 |

^a Solution excluding 13 stars with *Hipparcos* multiplicity flags.

^b Solution excluding 13 *Hipparcos* multiples plus T Tau N and RZ Cas.

REFERENCES

Boboltz, D. A., Fey, A. L., Johnston, K. J., Claussen, M. J., de Vegt, C., Zacharias, N., & Gaume, R. A. 2003, AJ, 126, 484

Claussen, M. J., Beresford, R., Sowinski, K., & Ulvestad, J. S. 1999, BAAS, 31, 1498

Fey, A. L., Boboltz, D. A., Gaume, R. A., Johnston, K. J., Garrington, S. T., & Thomasson, P. 2006, AJ, 131, 1084

Fey, A. L., et al. 2004, AJ, 127, 3587

Gambis, D., ed. 1999, 1998 IERS Annu. Rep. (Paris: Obs. Paris)

Hartkopf, W. I., Mason, B. D., Wycoff, G. L., & McAlister, H. A. 2001, Fourth Catalog of Interferometric Measurements of Binary Stars (Washington: USNO), <http://ad.usno.navy.mil/wds/int4.html>

Johnston, K. J., de Vegt, C., Florkowski, D. R., & Wade, C. M. 1985, AJ, 90, 2390

Johnston, K. J., de Vegt, C., & Gaume, R. A. 2003, AJ, 125, 3252

Johnston, K. J., Fey, A. L., Gaume, R. A., Claussen, M. J., & Hummel, C. A. 2004, AJ, 128, 822

Kovalevsky, J., et al. 1997, A&A, 323, 620

Lestrade, J.-F., Preston, R. A., Jones, D. L., Phillips, R. B., Rogers, A. E. E., Titus, M. A., Rioja, M. J., & Gabuzda, D. C. 1999, A&A, 344, 1014

Ma, C., et al. 1998, AJ, 116, 516

Mason, B. D., Wycoff, G. L., Hartkopf, W. I., Douglass, G. G., & Worley, C. E. 2001, AJ, 122, 3466

Perryman, M. A. C., et al. 1997, A&A, 323, L49

Walter, H. G., & Sovers, O. J., eds. 2000, Astrometry of Fundamental Catalogues: The Evolution from Optical to Radio Reference Frames (Berlin: Springer)